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Using radiation thermography and thermometry to evaluate crop water stress in soybean and cotton

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ABSTRACT

The use of digital infrared thermography and thermometry to investigate early crop water stress offers a producer improved management tools to avoid yield declines or to deal with variability in crop water status. This study used canopy temperature data to investigate whether an empirical crop water stress index could be used to monitor spatial and temporal crop water stress. Different irrigation treatment amounts (100%, 67%, 33%, and 0% of full replenishment of soil water to field capacity to a depth of 1.5 m) were applied by a center pivot system to soybean (*Glycine max* L.) in 2004 and 2005, and to cotton (*Gossypium hirsutum* L.) in 2007 and 2008. Canopy temperature data from infrared thermography were used to benchmark the relationship between an empirical crop water stress index ($CWSI_e$) and leaf water potential (Ψ_L) across a block of eight treatment plots (of two replications). There was a significant negative linear correlation between midday Ψ_L measurements and the $CWSI_e$ after soil water differences due to irrigation treatments were well established and during the absence of heavy rainfall. Average seasonal $CWSI_e$ values calculated for each plot from temperature measurements made by infrared thermometer thermocouples mounted on a center pivot lateral were inversely related to crop water use with r^2 values >0.89 and 0.55 for soybean and cotton, respectively. There was also a significant inverse relationship between the $CWSI_e$ and soybean yields in 2004 ($r^2 = 0.88$) and 2005 ($r^2 = 0.83$), and cotton in 2007 ($r^2 = 0.78$). The correlations were not significant in 2008 for cotton. Contour plots of the $CWSI_e$ may be used as maps to indicate the spatial variability of within-field crop water stress. These maps may be useful for irrigation scheduling or identifying areas within a field where water stress may impact crop water use and yield.

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1. Introduction

Crop sensing technologies have potential as tools for monitoring crop water status, predicting yields (Idso et al., 1978, 1980; Pinter et al., 1983), improving water use efficiency (Evett et al., 1996, 2001, 2006) and harvesting methods, and precisely managing irrigation (Wanjura et al., 1995). Useful information on crop canopy temperature and water relations can be derived from infrared thermography and thermometry. Infrared thermography has been used in agriculture as a non-invasive, versatile imaging tool to investigate biotic stresses (disease or insect infestation), and abiotic stresses (e.g., nutrient and water deficit). Chaerle et al. (2006) combined thermal and chlorophyll fluorescence imaging to study spatial and temporal heterogeneity of leaf transpiration and photosynthesis. These techniques helped identify pre-symptomatic responses (higher chlorophyll intensity co-located with thermal symptoms) and provided diagnosis of diseases (fungal and bacterial infections) and abiotic stresses not yet perceptible in visible spectrum images. Stoll et al. (2008) used an infrared camera to observe thermal responses in grapevine infected with a fungus well in advance of visible symptoms. Bulanon et al. (2009) fused digital and thermal images taken of the same area to improve the identification of fruit for robotic harvesters.

Studies involving the analysis of abiotic stresses with thermal imagery include those by Jones (1999) and Jones et al. (2002) in which field studies were designed to assess the consistency and repeatability of using thermal imagery to measure stomatal conductance in grapevine canopies. They concluded that thermography allows for semi-automated analysis of large areas of canopy with much more effective replication than can be achieved with porometry. Leinonen and Jones (2004) classified thermal images to identify leaf area, sunlit, and shaded parts of the canopy. Their methods provided improved estimates of temperature distribution across a canopy by separating out mixed pixels and reducing the effects of thermal contribution from background, and angle of view (Luquet et al., 2003).

Leaf water potential measurements became routine in the 1960s with the commercialization of pressure chambers (Turner, 1988)

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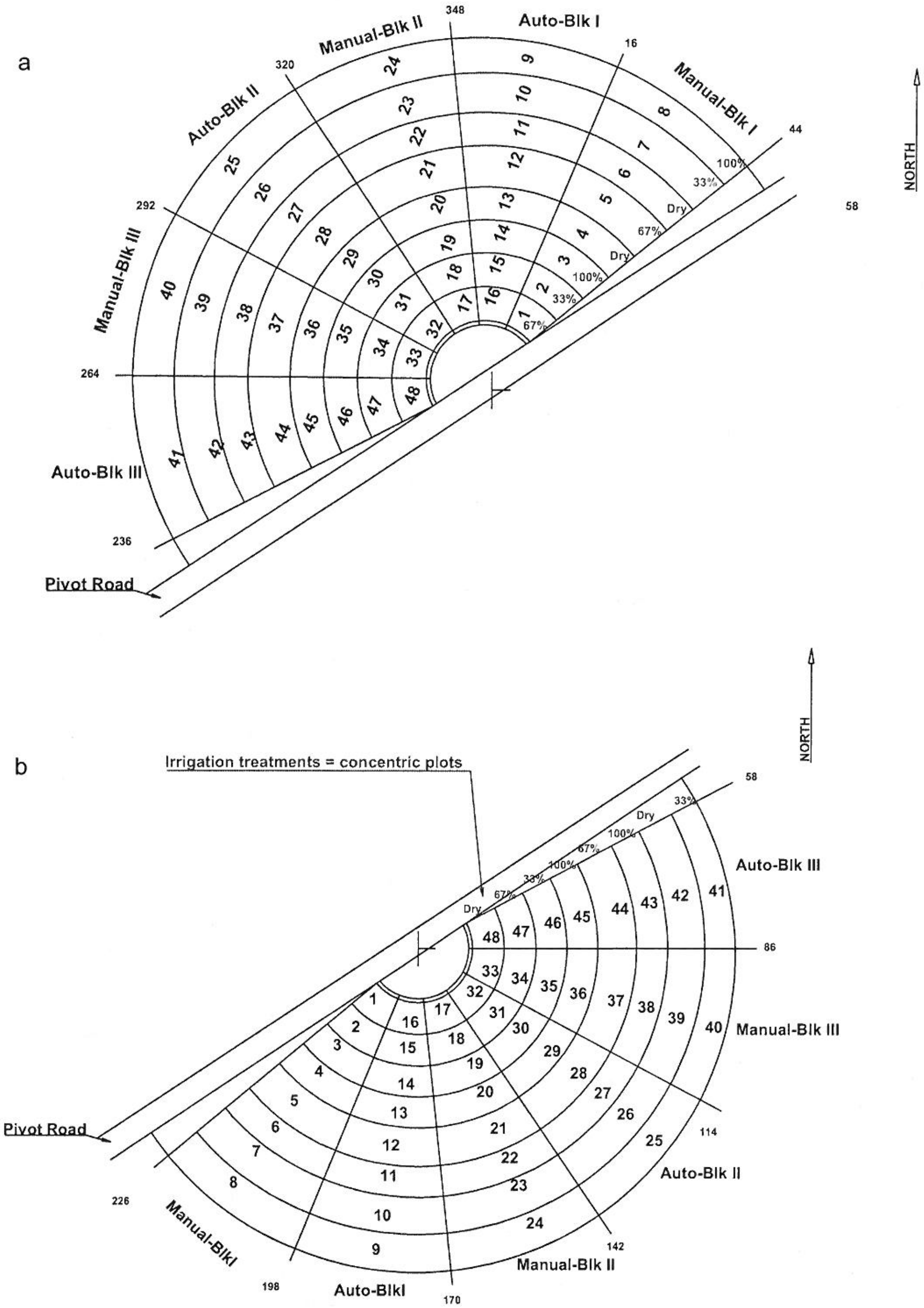

Fig. 1. Experimental layout under the 3-span center pivot system shown for the (a) 2004 growing season; and (b) the 2005 and 2007 growing seasons. Pie-slice-shaped sections are blocked by irrigation control method (manual vs. automatic). Each block contains all irrigation amount treatments with two replications, 100%, 67% and 33% of full replenishment of soil water to field capacity and a no-irrigation ((Dry) treatment, which are randomized radially within each section and run concentrically. (Not shown is the plot plan for the 2008 growing season. The north half of the pivot field was cropped, but the order of irrigation treatment amounts was different from that of 2004.)

once every 30 days. Access tubes were placed in a row in the center of each plot. The neutron probe was field calibrated to accuracy of better than 0.01 $m^3 m^{-3}$, resulting in separate calibrations from three distinct soil layers, Ap, Bt and Btca, using methods described by Evett (2008). Irrigations for the manual control treatment were applied on odd DOY, over 3 days of the week if necessary. Any rainfall occurring prior to irrigation of the total amount for the week was subtracted from the required total. Irrigations for the automatic control treatment were applied on even DOY. Seasonal crop water use (ET) in each plot was calculated using the soil water balance equation (Evett, 2002):

$$ET = P + I + F - \Delta S - R \quad (3)$$

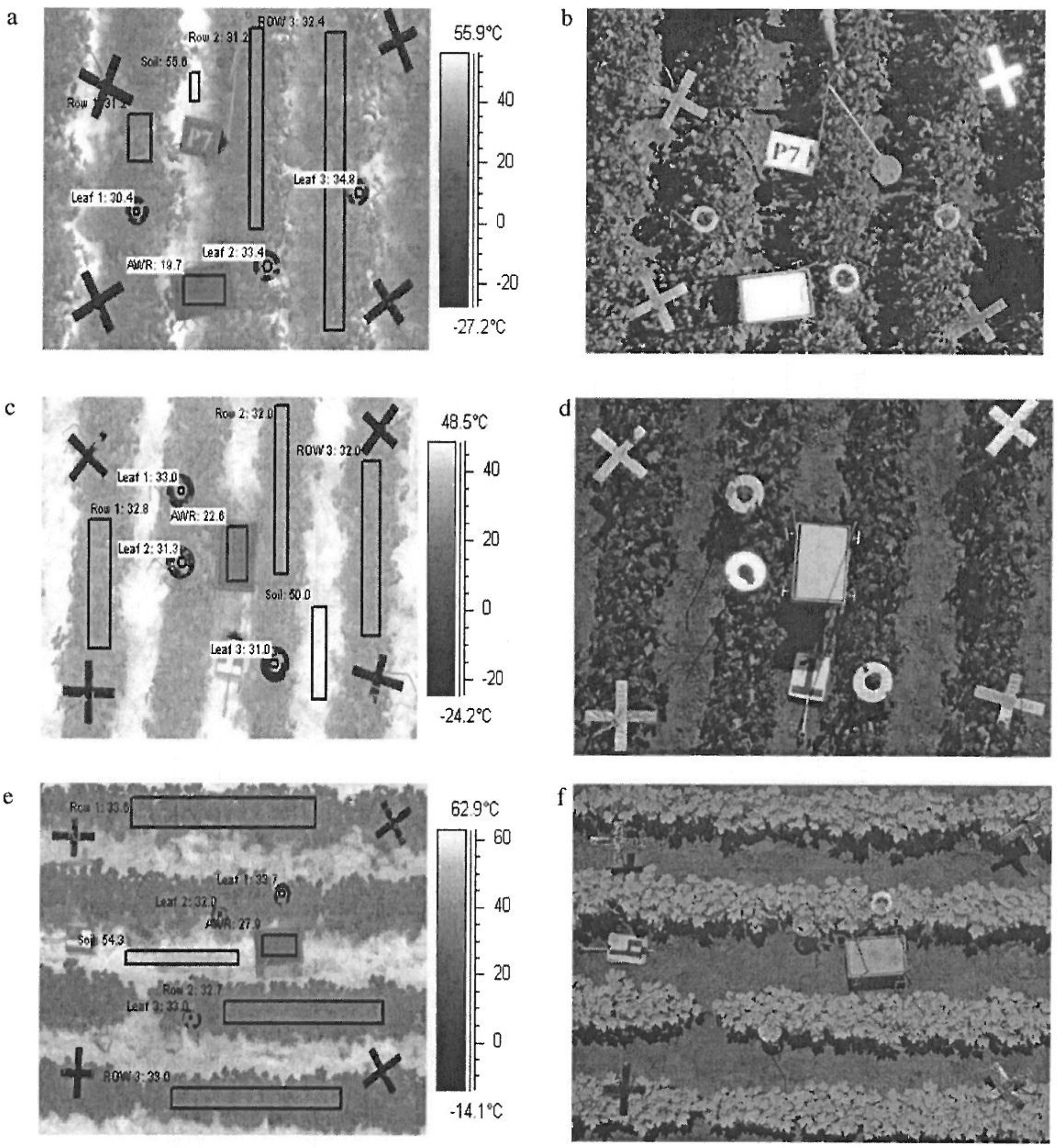

Fig. 2. Examples of thermal and corresponding digital RGB/IR-pass images taken from 7.0 m above grade in individual irrigation treatment plots. Rectangles shown are the polygons discussed in the text. Shown are average temperature of crop rows, the artificial wet reference (AWR), soil, and individual leaves for: (a) and (b) soybean 2005 (DOY 258), $I_{33\%}$; (c) and (d) cotton 2007 (DOY 247), $I_{0\%}$; and (e) and (f) cotton 2008 (DOY 213), $I_{100\%}$. (b and d) are from a digital RGB camera without filtering; and (f) is from a digital camera that is sensitive in the near infrared and was taken with a filter that excluded wavelengths > near infrared. Shaded soils ranged between approximately 30 °C and 42 °C, sunlit soils were generally >50 °C, and crop canopy temperatures within polygons were between 30 °C and 35 °C.

center of the field-of-view of the image when placed in a treatment plot. Canopy temperature for the $CWSI_e$ was determined by averaging three different polygon areas from different crop rows within a single thermal image (e.g., Fig. 2a, c, and e). It was assumed that this method would be similar to the canopy temperatures recorded by IRTs mounted on the moving center pivot system.

The extracted wet reference temperatures were average values for the unshaded areas of the wet reference body. The digital photographs were used to improve digital analysis and to discriminate between vegetative and soil pixels of similar temperature (example in Fig. 2b).

The empirical wet reference crop water stress index, $CWSI_e$, was calculated using Eq. (1), with T_w being the average temperature of the wet reference and T_{dry} being estimated by adding 5 °C to the maximum dry bulb temperature recorded. The $CWSI_e$ ranged from 0 (no stress) to nearly 1 (stressed), at which point T_c was nearly equal to T_{dry}. The $CWSI_e$ values calculated from thermal imagery represented a one-time-of-day measurement only and were not used to calculate the seasonal average $CWSI_e$ values discussed later.

2.4. Infrared thermometry

In all four years (2004–2008), the $CWSI_e$ was also determined using canopy temperature measurements obtained using IRTs. Sixteen IRTs (Exergen model IRT/c.5, Watertown, Mass.) with a 5:1 field of view were mounted on masts attached to the center pivot lateral, with two sensors facing into each treatment plot pointed towards the canopy at an oblique angle. One sensor was mounted at the outside edge of each plot and one sensor on the inside edge so that the sensors were aimed nearly towards each other from

Table 4
Average climatic data at midday (1200–1500 h), cumulative rainfall, total solar radiation, and daily reference evapotranspiration values from the Bushland ARS research meteorological station on days when leaf water potential and thermal images were taken.

Sampling date (DOY)	Average air temperature (°C)	Average relative humidity (%)	Average wind speed at 2 m height ($m\,s^{-1}$)	Total solar radiation ($MJ\,m^{-2}\,d^{-1}$)	Cumulative rainfall two weeks prior to sampling date (mm)	ET_o ($d\,mm^{-1}$)
August 3, 2005 (215)	31.8	26.0	3.8	22.5	0.0	7.8
August 25, 2005 (237)	31.2	45.5	6.0	18.0	51.9	6.2
September 15, 2005 (258)	23.2	40.3	3.0	17.7	5.3	5.0
August 11, 2007 (223)	32.6	30.8	5.0	19.3	17.0	8.7
August 23, 2007 (240)	30.0	40.7	6.8	25.9	8.6	8.3
September 4, 2007 (247)	28.0	38.9	4.0	21.0	9.6	5.8
September 13, 2007 (256)	24.0	63.8	3.0	20.4	29.2	4.5
July 21, 2008 (203)	32.3	25.5	6.8	21.2	28.2	8.2
July 31, 2008 (213)	34.8	15.5	2.8	19.8	21.6	7.1
September 15, 2008 (261)	24.5	44.4	1.8	17.5	11.2	3.9

opposite sides of the plot to reduce sun angle effects on the average temperature. The center pivot passed over each plot during different times of the day, which required a method to determine the canopy temperature, T_s, at 13:00 CST in order to calculate the $CWSI_e$ at 13:00 CST. We used the scaling procedure described by Peters and Evett (2004b):

$$T_s = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \tag{4}$$

where T_e (°C) was the predawn canopy temperature; T_{ref} (°C) was the reference canopy temperature at the same time interval as T_s (°C) (i.e., 13:00 CST); $T_{rmt,t}$ was the one-time-of-day canopy temperature measurement at the plot (remote location, denoted by subscript rmt) at any daylight time t measured by the IRTs on the pivot lateral; and $T_{ref,t}$ (°C) was the measured reference temperature for the time t that the plot (remote) temperature measurement was taken. The diel $T_{ref,t}$ was obtained using stationary IRTs mounted on fixed masts in the fully irrigated treatment plots. Plot-mean scaled canopy temperature measurements, T_s, for each treatment plot were substituted for crop canopy temperature, T_c, in Eq. (1). Signals from IRTs were measured and recorded every 10 s and averaged and stored each min.

Average seasonal $CWSI_e$ values for each of the 48 plots were calculated from data measured on the days the pivot moved using scaled canopy temperatures (T_s) estimated for 13:00 CST. Again, the $CWSI_e$ was calculated using T_{dry} as the maximum daily dry-bulb temperature (T_{max}) + 5 °C. The wet reference temperature, T_w, was estimated using Eq. (2). The value of γ in Eq. (2) was estimated at a barometric pressure of 88.91 kPa. In a sub-study, we evaluated whether T_{dry} should be used in place of T_a in Eq. (2) by comparing the result of Eq. (2) to measurements of physical wet reference surface temperatures.

2.5. Data analysis

Linear regressions of $CWSI_e$ vs. leaf water potential were developed using temperature data extracted from thermal images. The average seasonal $CWSI_e$ values, calculated using temperature data measured using IRTs on the pivot lateral and with T_w estimated at 13:00 CST (Eqs. (3) and (4)), were linearly regressed against irrigation treatment amounts, seasonal water use (obtained by soil water balance), and crop yield. An analysis of variance was used to determine if irrigation amounts (0, 33, 67, and 100%) had a significant impact on the $CWSI_e$ when grouped by irrigation control method (manual vs. automatic). The Bonferroni t-test was used to compare whether mean $CWSI_e$ values were the same across irrigation treatment amounts and irrigation scheduling methods (manual or automatic). Analysis was performed using the ANOVA and SAS PROC MIXED procedures (SAS Institute Inc., 2007). We tested the homogeneity of regression coefficients for the manual and automatic methods of irrigation scheduling, when regressing water use and crop yields against the $CWSI_e$, using methods discussed by Gomez and Gomez (1984). All significant differences are reported at the 5% probability level.

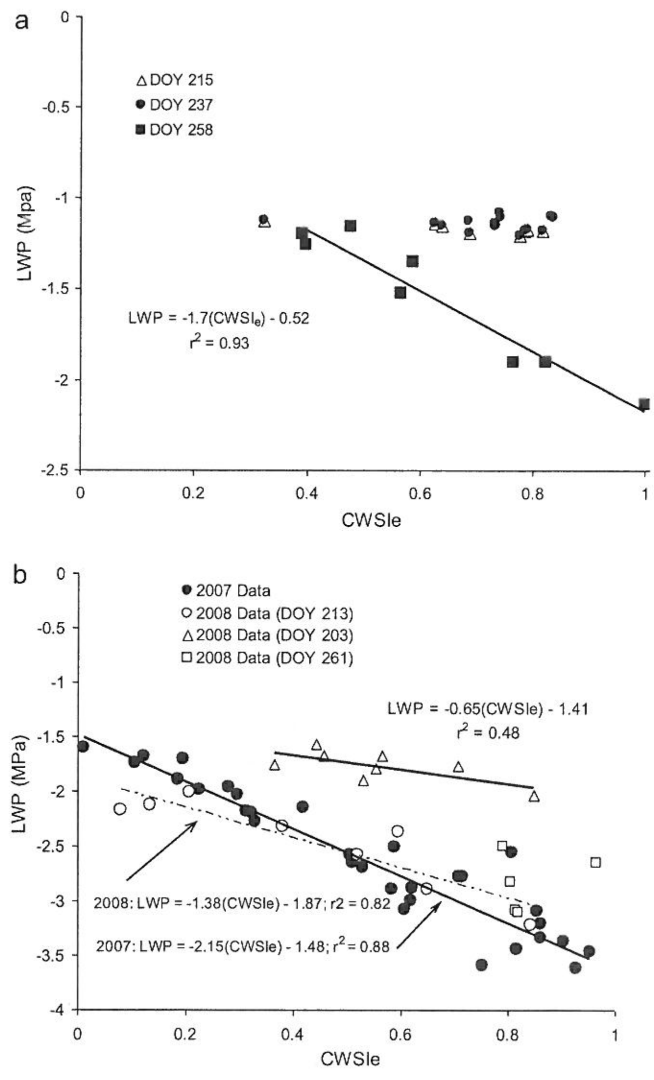

Fig. 3. The inverse relationship between leaf water potential taken at midday and the empirical crop water stress index, $CWSI_e$ calculated using temperatures extracted from thermometric images in treatment plots 1–8 during the growing season: (a) 2005, soybean; and (b) 2007 and 2008, cotton.

3. Results and discussion

3.1. Irrigations, crop water use and meteorological data

Average irrigations, change in soil water content, seasonal ET_c and climatic data are summarized in Table 3. For soybean, average irrigation levels and average seasonal ET_c across irrigation treatment amounts were greater for the manual method. The 2004 growing season experienced below average temperatures and above average rainfall, while in 2005, the reverse occurred with total rainfall being nearly 50% less (Table 3). Overall soybean ET_c was higher in 2004 than in 2005, and initial soil water levels for both years were higher than the final soil water levels.

Reviewing climatological data for the cotton growing seasons, extreme weather conditions prevailed in 2008. During the months of May and June, high winds and elevated daily air temperatures resulted in a 6% increase in ET_o as compared to the same period in 2007. A cumulative rainfall amount of 70 mm occurred from August 11 (DOY 224) through August 21 (DOY 234) in 2008. During this time, the sky was consistently overcast. In August of 2007, 56% of the rainfall occurred on the second day of the month (DOY 214) followed by two weeks of dry hot weather. Also of notable difference, in 2007, maximum daily air temperatures and ET_o were highest for the months of June through August. In contrast, the average maximum daily air temperatures for July and August in 2008 dropped nearly 3.5 °C and 2 °C from June's average maximum daily air temperature. Soil water levels were higher at the end of growing season 2008 than at its start.

Microclimatological measurements (Table 4) for each sampling day showed that air temperature was highest during the first two sampling days of the season and decreased by between 5 °C and 7 °C on the last sampling day. DOY 240 in 2007 was periodically cloudy, and care was taken to capture thermal images only when the clouds were not blocking the sun. The greatest maximum average air temperature and reference evapotranspiration (ET_o) occurred in July and August for each growing season when the average midday temperatures were >30 °C and either wind speed was nearly 5.0 m s^{-1} or relative humidity was <30%.

3.2. Thermal imagery, $CWSI_e$ and Ψ_L

Thermal and digital images taken from the hydraulic lift over the 8 treatment plots enabled a clear distinction between shaded and sunlit soil and shaded and sunlit vegetation and their corresponding temperatures (examples for 2005, 2007 and 2008 shown in Fig. 2). For the sampling days listed in Table 2, the $CWSI_e$ calculated from digital thermal imagery over plots 1–8 were compared with corresponding Ψ_L measurements. On most sampling days, Ψ_L

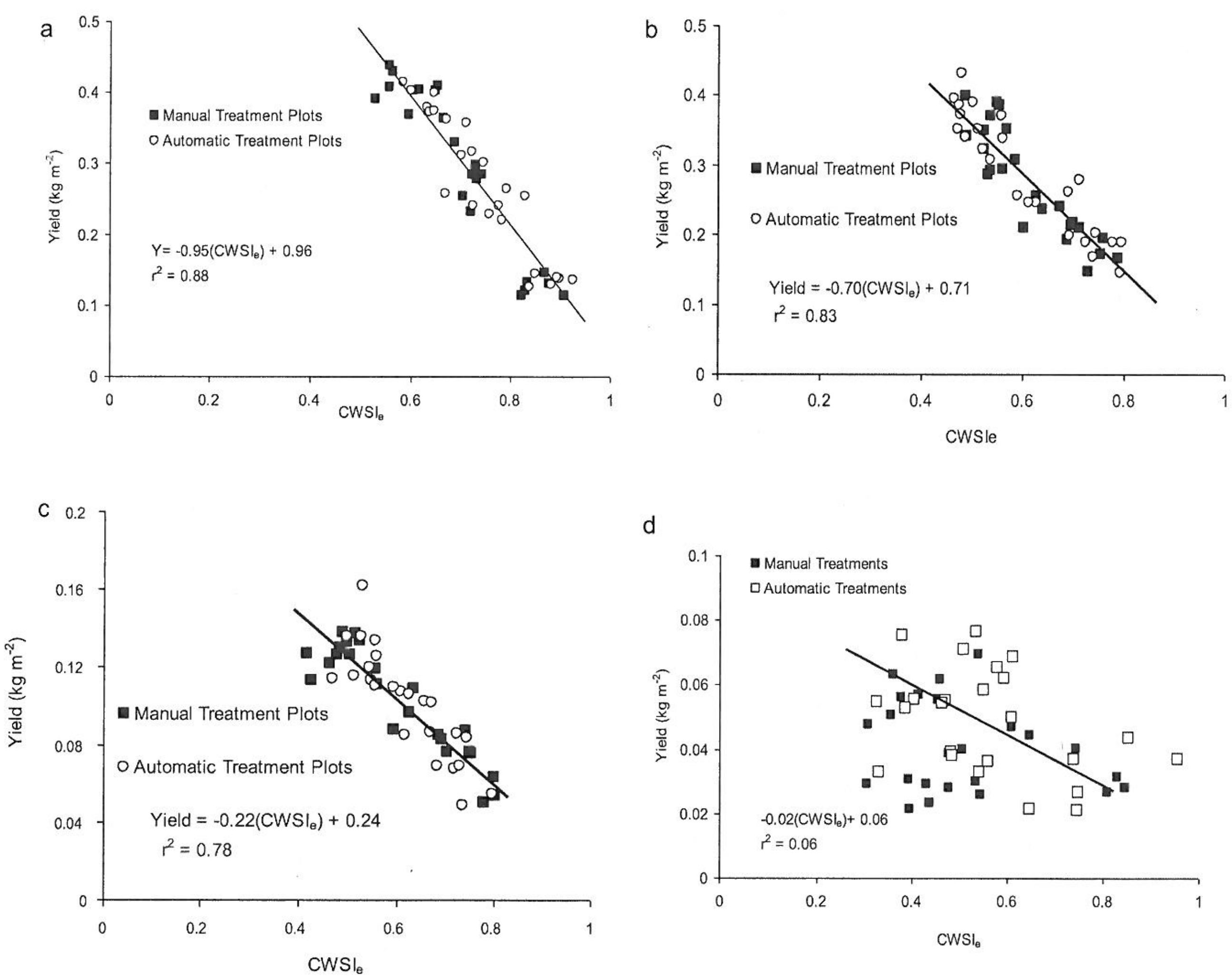

Fig. 5. Inverse linear correlations between the season-mean $CWSI_e$ and yields for both manually and automatically irrigated plots: dry grain yields for (a) soybean, 2004; (b) soybean 2005; and lint yields for (c) cotton, 2007; and (d) cotton, 2008.

in soybean yields in 2004 and 2005, respectively (Fig. 5a and b). A single regression line was used to represent the data since the slopes between manual and automatic control treatment plots were not significantly different with 44 degrees of freedom for the 5% level of significance. In general, the plots experiencing the smallest seasonal average $CWSI_e$ resulted in the greatest water use and yields. This same trend was reported by Nielsen (1990) for soybean grown in Akron, Colorado under irrigation scheduling based on varying CWSI values. Similar to our results, Dogan et al. (2007) reported yields in the range of 0.36–0.37 kg m^{-2} for fully irrigated soybean ($I_{100\%}$) and average yields of 0.19 kg m^{-2} ($I_{50\%}$), 0.10 kg m^{-2} ($I_{25\%}$), and 0.03 kg m^{-2} ($I_{0\%}$) for deficit irrigation treatment levels.

For cotton, the seasonal mean $CWSI_e$ explained 78% of the yield variations for all treatment plots in 2007 (Fig. 5c). Again, there was no significant difference between the regression coefficients for the manual and automatic methods of irrigation with 44 degrees of freedom for the 5% level. Similar to soybean, cotton lint yield was significantly related to growing season interannual variability. The 2007 linear relationship between lint yield (kg m^{-2}) and the seasonal mean $CWSI_e$, Yield = $-0.22CWSI_e + 0.24$, was similar to the lint yield (LY, kg m^{-2}) relationships reported by Reginato (1983), LY = -0.21CWSI + 0.18, and Howell et al. (1984), LY = -0.19CWSI + 0.18, for conventional row cotton with 1.0 m spacing, where the CWSI was calculated using the empirical method of Idso et al. (1981).

Although, the 2008 average season-long $CWSI_e$ increased as the irrigation treatment amounts decreased, there was not a consistent negative linear relationship between yield and the $CWSI_e$ (Fig. 5d). The slopes between the manual and automatic treatment plots were not significantly different and were therefore represented by a single slope. Cotton production during this growing season was affected by extreme weather conditions. Hot, dry winds at emergence slowed emergence and plant establishment, while heavy rainfall in mid August encouraged vegetative growth and hampered boll filling, particularly in the fully irrigated treatment s. The combination of these impediments reduced fully irrigated yields by 70% from 2007. Although the average $CWSI_e$ values were inversely related to average lint yields when the fully irrigated treatment plots ($I_{100\%}$) were considered outliers (O'Shaughnessy and Evett, 2010), cotton yields from individual treatment plots were highly variable and not well predicted by the $CWSI_e$.

To demonstrate how soon in the irrigation season the relationship between the temporal-mean $CWSI_e$ and crop yield may be useful, the crop yield was regressed against a progressive average of the $CWSI_e$ calculated from the first date that the pivot moved to progressive dates on which it moved, including at each successive date all the data from the first date to that date. The coefficient of determination, r^2, of the regression analysis was plotted against the number of days after the start of irrigation treatment applications (Fig. 6). The approximate time required to establish a stable correlation between crop yield and $CWSI_e$ was approximately 5 days

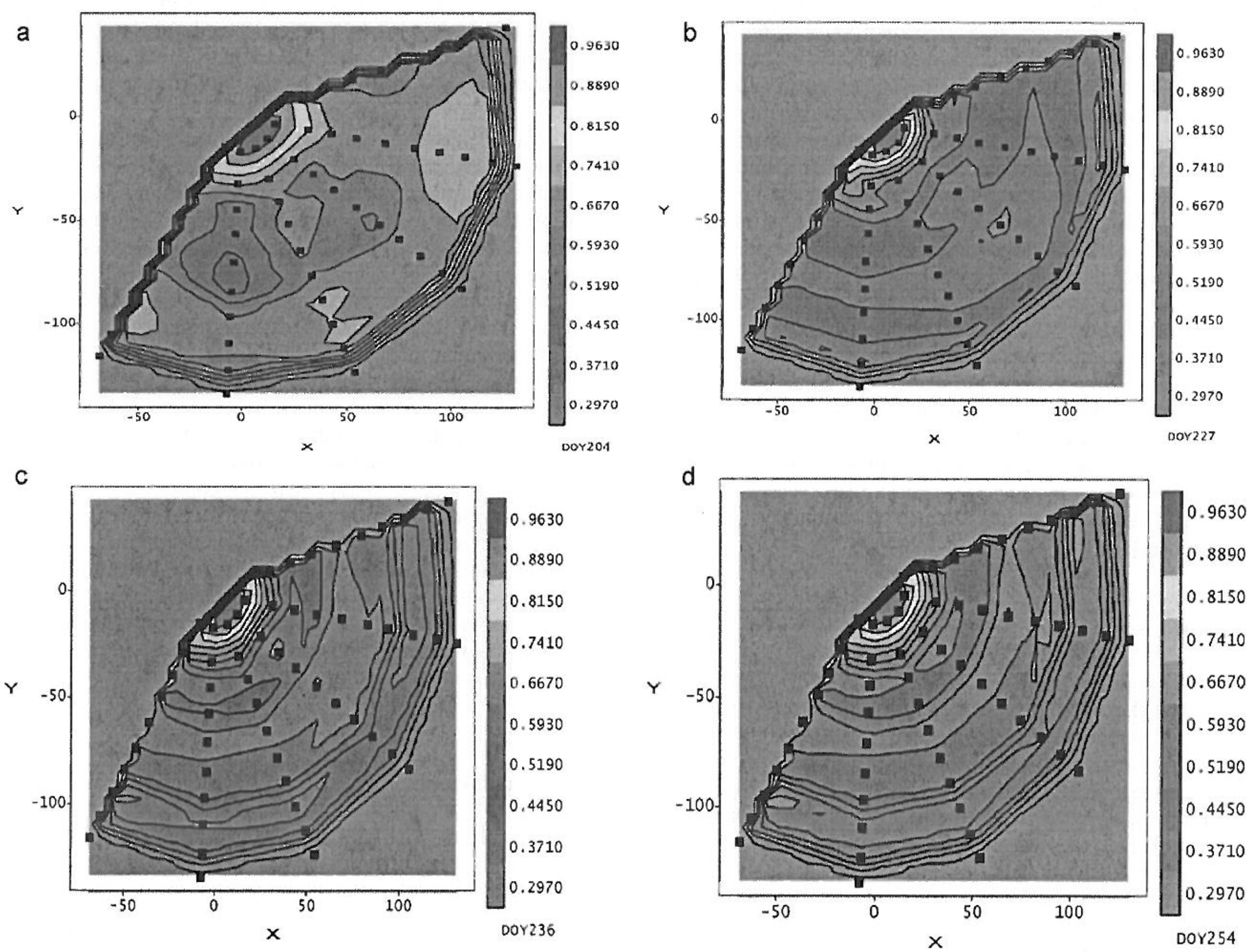

Fig. 7. Spatial map of average empirical $CWSI_e$ for cotton over growing season 2007, averaged values from DOY 198 through listed date: (a) DOY 204, 6 days after start of irrigation treatments; (b) DOY 227, 29 days after start of irrigation treatments; (c) DOY 236, 38 days after start of irrigation treatments; and (d) DOY 254, 2 weeks after halting irrigation treatments. Spatial map for soybean crops 2004, 2005 and for cotton 2008 are not shown.

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